J3.18 WATER BALANCE COMPUTATIONS OF SEASONAL CHANGES IN TERRESTRIAL WATER STORAGE: CASE STUDY FOR THE MISSISSIPPI RIVER BASIN AND METHODOLOGY VALIDATION AGAINST OBSERVATIONS FROM ILLINOIS.

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1. INTRODUCTION

Terrestrial water storage is an essential part of the hydrological cycle, which encompasses crucial elements of the climate system such as soil moisture, groundwater, snow, and ice cover. Intraseasonal variations of the terrestrial water storage play an important role for the predictability of the climate system (Koster et al. 2000), may feed back on the regional precipitation climate (Betts et al. 1996, Schär et al. 1999) and are believed to be critically affected by climate change (Wetherald and Manabe 1999, Seneviratne et al. 2002). However, regarding continental-scale soil-moisture and groundwater variations, only little information is available from observations.

The water-balance method allows to estimate monthly variations in terrestrial water storage using three main variables: the water vapour flux convergence, the precipitable water content, and river runoff. The two first variables are available with high resolution and good accuracy in present reanalysis data, and river runoff is commonly measured in most parts of the world.

The basic concept of using atmospheric data to estimate the terrestrial water balance was investigated in early studies using raw radiosonde data (e.g. Starr and Peixoto 1958, Rasmusson 1968, Alestalo 1983). It has received more attention in recent years, thanks to the availability of high-resolution reanalysis data which have been shown to improve the accuracy of such computations (e.g. Trenberth and Guillemot 1995, Oki et al. 1995, Matsuyama and Masuda 1997, Yeh et al. 1998, Berbery and Rasmusson 1999, Masuda et al. 2001).

Here we test this approach in a 10-year (1987-1996) case study for the Mississippi river basin using ERA-40 reanalysis data from the European Centre for Medium-Range Weather Forecasts (atmospheric water vapour flux and precipitable water content) and runoff observations from the United States Geological Survey (USGS).

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2. METHODOLOGY

2.1 The Water Balance Equations

Peixoto and Oort (1992) provide a good review on this topic. Here we briefly present the combined terrestrial and atmospheric water-balance approach as used in this study.

The terrestrial branch of the hydrological cycle is governed by the following equation:

$$\frac{\partial S}{\partial t} = -Rs - Ru + (P - E) \qquad [1]$$

with:

S: Basin storage (soil moisture+groundwater+surface water+snow storage)
Rs: Surface Runoff
Ru: Subterranean Runoff
P: Precipitation
E: Evapotranspiration

The atmospheric water balance is expressed as follows:

$$\frac{\partial W}{\partial t} + \frac{\partial Wc}{\partial t} = -\nabla_H Q - \nabla_H Q_c - (P - E) \qquad [2]$$

with:

W: Column storage of water vapour (precipitable water)
W_c: Column storage of liquid and solid water
Q: Vertically integrated 2-dimensional water vapour flux
Q_c: Vertically integrated 2-dimensional water flux (solid + liquid)

Combining equations [1] and [2] with the assumptions:
- Ru << Rs, E, P
- Wc, Qc << W, Q ,

leads to the following equation for the change in basin storage:

$$\frac{\partial S}{\partial t} = -\frac{\partial W}{\partial t} - \nabla_H Q - Rs \qquad [3]$$

In this combined equation, the monthly variations in terrestrial water storage of the studied region can be expressed as the sum of three terms only: the atmospheric water vapour flux convergence, the changes in precipitable water content, and the measured river runoff. The term representing the changes in precipitable water content is usually negligible for annual means, but not for monthly means, particularly during the spring and fall (Rasmusson 1968).

2.2 Employed Datasets

2.2.1 Water vapour flux and precipitable water content

The vertically integrated water vapour fluxes and precipitable water content are taken from the latest ECMWF reanalysis data product, ERA-40 (Simmons and Gibson 2000). The ERA-40 project, which is still in its running phase, aims at creating a complete reanalysis dataset covering more than 40 years (from mid-1957 to 2001). Here we use 10 years of data, covering the period 1987 to 1996.

The ERA-40 model has a T159 spherical harmonic representation for the atmospheric dynamical fields and for temperature, and a grid point representation for humidity and cloud variables, using the so-called reduced Gaussian grid (Hortal and Simmons 1991), with an almost uniform distribution of grid points on the sphere, with a grid-spacing of 112 km. There are 60 levels in the vertical, with a hybrid sigma-pressure coordinate, going from the surface to 0.1 hPa. A description of the computation of the water vapor flux divergence can be found in Seneviratne et al. (2003).

The fields of water vapour flux divergence and precipitable water content are averaged for the chosen domains using latitude-longitude quadrilaterals, following

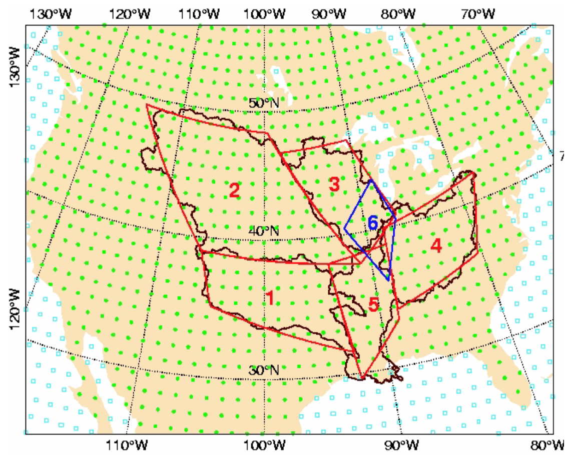

Fig 1. Five major Mississippi subbasins and their approximation in the ECMWF reanalysis model (domains 1-5); domain 6 approximately covers the State of Illinois. Model grid points are represented by closed green circles (land) and open blue squares (sea).

Table 1: Quadrilaterals used for the computation of the domains' mean ERA-40 fields

	Domain	Area [km^2]
1	Arkansas-Red	604,054
2	Missouri	1,299,229
3	Upper Mississippi	512,722
4	Ohio	462,521
5	Lower Mississippi	382,664
6	Illinois	203,549

the same methodology as Betts et al. (1998, 1999) and Betts and Viterbo (2003). The domains include the same 5 Mississippi subbasins as in Betts and Viterbo (2003), as well as an additional domain approximately covering the State of Illinois. Domain 1 comprises the Arkansas and Red River basins, domain 2 the upper Missouri basin, domain 3 the upper Mississippi basin, domain 4 the Ohio basin, domain 5 the lower Mississipppi and Tennessee River basins (in a somewhat poorer approximation), and domain 6 the State of Illinois. The 6 domains are pictured in Figure 1 and shortly described in Table 1.

2.2.2 Surface Streamflow Data

We use surface streamflow data from the United States Geological Survey (USGS).

For the Mississippi subbasins, measurements from the following 6 stations are used: Arkansas River at Van Buren, Red River at Index, Missouri River at Kansas City, Missouri River at St. Louis, Illinois River at Metropolis, and Mississippi River at Vicksburg. These stations are the same as the ones used in Betts et al. (1999); the streamflow of domains 1-5 and of the whole Mississippi river basin is computed in the same way as in their study.

Note that there are no actual runoff measurements for domain 5 (Mississippi and Tennessee River basin), where runoff can only be computed as the difference between the total runoff of the whole Mississippi river basin (station Vicksburg) and the runoff measured for the other subbasins. The computed monthly runoff variations present unrealistic spikes (not shown) which are likely due to the very small size of the considered drainage basin and the cumulated error uncertainties. For this reason, the water-balance computations for this domain appear quite erratic and are not presented here.

For the computation of the mean runoff for the State of Illinois, we use the same proceeding as Yeh et al. (1998). Daily discharge measurements are used from the three following hydrological stations: Illinois River at Valley city, Rock River near Joslin, and Kaskaskia River near Venedy Station. These three streamflow-gauging stations are located as far downstream as possible within the drainage areas along the three major rivers in Illinois (Yeh et al. 1998). Their integrated monthly discharges are weighted by drainage areas in order to obtain an estimation of average areal runoff in Illinois.

3. RESULTS

3.1 Computed changes in terrestrial water storage

Figures 2 and 3 display the computed water-balance estimates of the monthly changes in terrestrial water storage for the Mississippi subbasins Arkansas-Red, Missouri, Upper Mississippi and Ohio (domains 1-4),

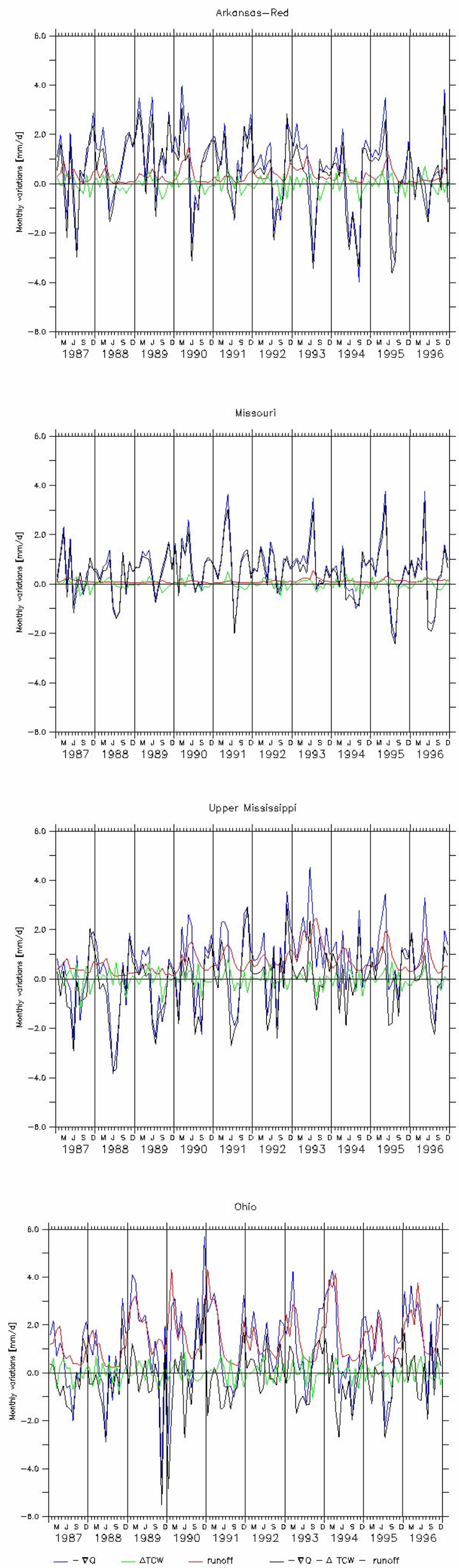

Fig 2. Water Balances for the Arkansas-Red (domain 1), Missouri (domain 2), Upper Mississippi (domain 3) and Ohio (domain 4) river basins [mm/d].

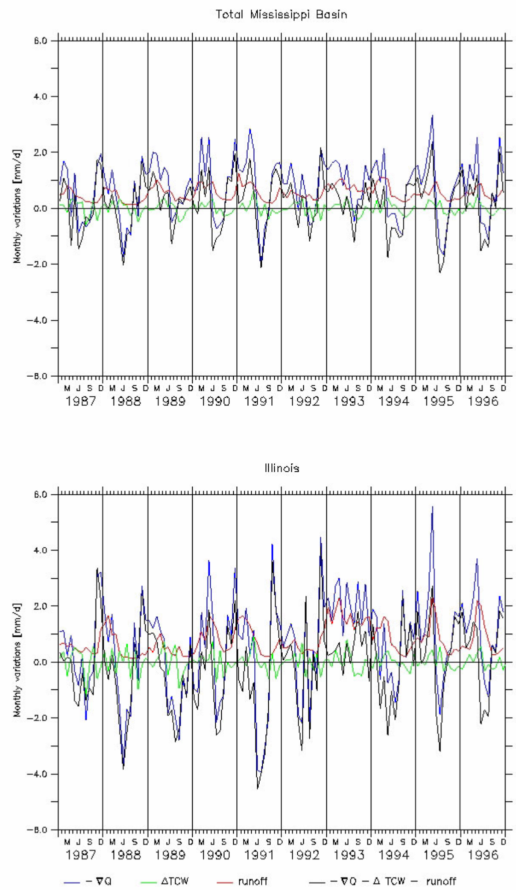

Fig 3. Water Balances for the whole Mississippi river basin (sum of domains 1-5) and Illinois (domain 6) [mm/d].

for the total Mississippi river basin (sum of domains 1-5), and for Illinois (domain 6).

For most domains the estimates of the changes in terrestrial water storage mostly follow the water vapor flux divergence, while the changes in precipitable water content and runoff are generally comparatively negligible.

An exception is the Ohio river basin, where river runoff has about the same magnitude as the atmospheric moisture divergence and is in general highly correlated with it. As noted by Berbery and Rasmusson (1999), the Ohio river basin is probably the most complex of all Mississippi basins due to important orographic effects from the Appalachian Mountains; it is characterized by the heaviest precipitation in the whole Mississippi River basin, frequently leading to winter and spring flood events. As most of the atmospheric moisture convergence over this domain appears to go into river runoff, the computed changes in terrestrial water storage are a mere residual of two large values and may be rather inaccurate.

In the other domains, the temporal evolution of the storage estimates appears reasonable and is in general characterized by a clear seasonal cycle with storage depletion in spring and summer, and recharge during the rest of the year.

3.2 Validation against Illinois observations

Illinois has a unique and comprehensive collection of hydrological datasets, including measurements of soil moisture, groundwater, and snow cover. Therefore, it is an ideal region for the validation of the methodology presented in this study.

Here we use soil moisture data of the Illinois State Water Survey (ISWS) (Hollinger and Isard 1994), shallow well data from the ISWS Water and Atmospheric Resource Monitoring (WARM) Program (Changnon et al. 1988) and snow measurements from the Midwest Regional Climate Center (MRCC). The computation of the total terrestrial water storage in Illinois from these datasets is described in detail in Seneviratne et al. (2003).

Figure 4 displays the evolution of the observed soil moisture, groundwater storage and snow water storage in Illinois for the years 1987-1996. Note that the soil moisture dataset used here ends in August 1996.

The main components of the total terrestrial water storage in Illinois are soil moisture and groundwater, while the contribution of the snow reservoir is comparatively negligible. Soil moisture and groundwater are characterized by very similar behaviours in most years. The late spring drought of 1988 and the summer flood of 1993 can be for instance easily recognized in both datasets. As far as the monthly variations are concerned (Figure 5), changes in soil moisture and groundwater are again of the same order of magnitude, while the contribution of the snow reservoir is negligible in comparison. Note that the peaks in soil moisture tend to precede those in groundwater storage.

Figure 6 shows a comparison between the water-balance estimates of the variations in terrestrial water storage for Illinois and the available observations. The estimates are close to the observations in most years, with the exception of 1989 and 1990 which are not well represented. Note that important features such as the drought of 1988 and the flood of 1993 are well captured. The mean climatology is also well represented for the years investigated (Figure 7).

The integration of the computed estimates in order to obtain absolute values of the terrestrial water storage

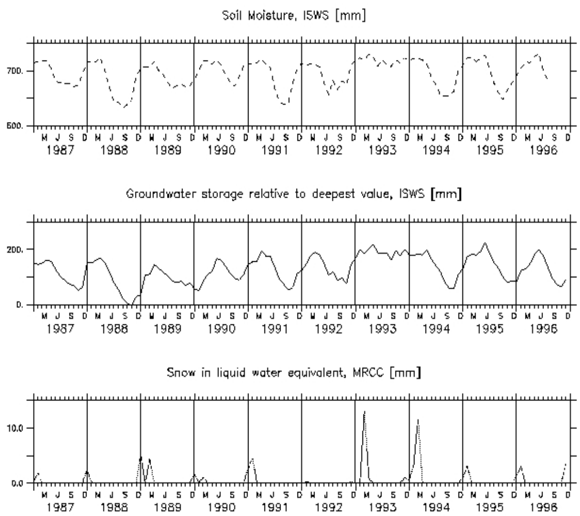

Fig 4. Observations [mm] of soil moisture, snow liquid water equivalent and groundwater storage in Illinois (1987-1996).

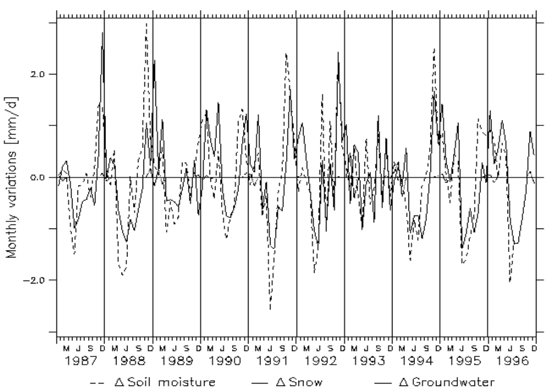

Fig 5. Monthly variations [mm/d] of the observations of soil moisture, snow liquid water equivalent and groundwater storage in Illinois (1987-1996).

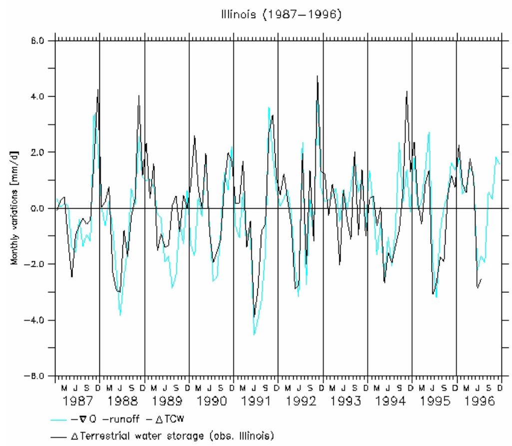

Fig 6. Computed water-balance estimates of variations in terrestrial water storage in Illinois (domain 6) compared with observations [mm/d].

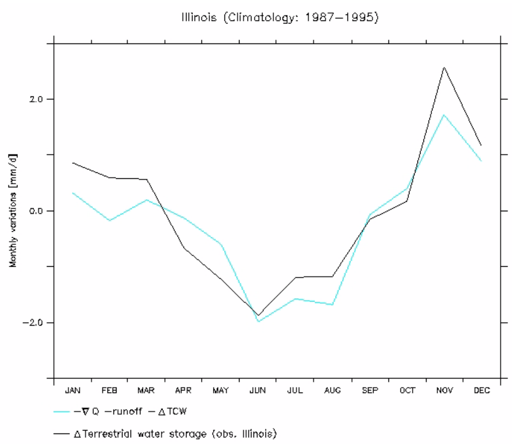

Fig 7. Climatology of the computed water-balance estimates of variations in terrestrial water storage in Illinois (domain 6) compared with observations for the years 1987-1995 [mm/d].

also appears to be possible, provided a measurement of the spring storage level is available (see Seneviratne et al. 2003). In regions where both soil moisture and snow cover measurements are available, estimates of variations in the groundwater level could possibly be provided.

Further results and a more detailed discussion of these findings are given in Seneviratne et al. (2003).

4. SUMMARY AND CONCLUSIONS

This study investigates the feasibility of estimating monthly variations in terrestrial water storage from water-balance computations using ERA-40 reanalysis data and conventional runoff data. The estimates computed for various subbasins of the Mississippi basin appear realistic and the values for Illinois show very good agreement with the available observations. The mean seasonal cycle is well represented for the studied period and the interannual variability is in general well captured.

An important result is that the critical domain size for water-balance computations using high resolution reanalysis data appears to be much smaller than for raw radiosonde data, such as in the studies by Rasmusson (1968, 1971). The Illinois domain has a size of only $\sim 2 \times 10^5$ km^2 and is shown to be suitable for the computation of the water-balance estimates. Yeh et al. (1998) come to similar conclusions in their study of the hydroclimatology of Illinois. It is possible that even smaller domains might still provide accurate results.

On the whole, these results are very promising and suggest that the employed methodology can give accurate estimates of changes in terrestrial water storage for large river basins. Although a comparison against other data sets (such as the NCEP or ERA-15 reanalyses) has not yet been conducted, it is likely that the high spatial resolution of the ERA-40 reanalysis is important for the high quality of the results.

One should stress however that the validation has been realised for a region with flat and homogeneous terrain, and that issues relative to horizontal or vertical homogeneities could therefore not be tackled. It is possible that this methodology might not be as accurate for regions presenting more heterogeneity or other climatic characteristics.

As mentioned in Section 2.2, the ERA-40 reanalysis project is still in its running phase. Once the full reanalysis data has been produced, it will be possible to compute water-balance estimates of changes in terrestrial water storage for the whole 40 year period. As runoff is available for these years for most major river basins, it will therefore be possible to obtain such estimates for various regions of the world. Further validation studies for regions where observations of some components of the terrestrial water storage are available would be needed in order to confirm the reliability of the employed method for other climatic and terrain conditions.

The presented method might also be useful for a cross-validation with the results of the on-going Gravity Recovery and Climate Experiment (GRACE; see Wahr et al. 1998, Rodell and Famiglietti 1999), which aims at the gravimetric estimate from space of changes in terrestrial water storage for the whole globe.

5. REFERENCES

Alestalo, M., 1983: The atmospheric water vapour budget over Europe. In: *Variations in the Global Water Budget*, A. Street-Perrot et al. (eds.), pp. 67-79. D. Reidel Publishing Company.

Berbery, E.H., and E.M. Rasmusson, 1999: Mississippi moisture budgets on regional scale. *Mon. Wea. Rev.*, **127**, 2654-2673.

Betts, A.K., J. H. Ball, A.C.M. Beljaars, M.J. Miller and P.A. Viterbo, 1996: The land-surface atmosphere interaction: A review based on observational and global modeling perspectives. *JGR-Atmospheres*, **101** (D3), 7209-7225

Betts, A.K., P. Viterbo, and E. Wood, 1998: Surface energy and water balance for the Arkansas-Red River basin from the ECMWF reanalysis. *J. Climate*, **11**, 2881-2897.

Betts, A.K., J.H. Ball, and P. Viterbo, 1999: Basin-scale surface water and energy budgets for the Mississippi from the ECMWF reanalysis. *JGR-Atmospheres*, **104** (D16), 19’293-19’306.

Betts, A.K., and P. Viterbo, 2003: River basin budgets from ERA-40. in preparation.

Changnon, S.A., F.A. Huff, and C.F. Hsu, 1988: Relations between precipitation and shallow groundwater in Illinois. *J. Climate*, **1**, 1239-1250.

Hollinger, S.E., and S.A. Isard, 1994: A soil moisture climatology of Illinois. *J. Climate*, **4**, 822-833.

Hortal, M., and A.J. Simmons, 1991: Use of reduced Gaussian grids in spectral models. *Mon. Wea. Rev.*, **119**, 1057-1074.

Koster, R.D., M.J. Suarez and M. Heiser, 2000: Variance and predictability of precipitation at seasonal-to-interannual timescales. *J. Hydrometeor.*, **1**, 26-46

Masuda, K., Y. Hashimoto, H. Matsuyama, and T. Oki, 2001: Seasonal cycle of water storage in major river basins of the world. *Geophys. Res. Lett.*, **28** (16), 3215-3218.

Matsuyama, H., and K. Masuda, 1997: Estimates of continental-scale soil wetness and comparison with the soil moisture data of Mintz and Serafini. *Clim. Dyn.*, **13**, 681-689.

Oki, T., K. Musiake, H. Matsuyama, and K. Masuda, 1995: Global atmospheric water balance and runoff from large river basins. *Hydrological Processes*, **9**, 655-678.

Peixoto, J.P., and A.H. Oort, 1992: Physics of climate. Am. Inst. of Phys. Press, Woodbury, New York.

Rasmusson, E.M., 1968: Atmospheric water vapor tranport and the water balance of North America. II. Large-scale water balance investigations. *Mon. Wea. Rev.*, **96**, 720-734.

Rasmusson, E.M., 1971: A study of the hydrology of eastern North America using atmospheric vapor flux data. *Mon. Wea. Rev.*, **99**, 119-135.

Rodell, M., and J.S. Famiglietti, 1999: Detectability of variations in continental water storage from satelitte observations of the time dependent gravity field. *Wat. Res. Res.*, **35** (9), 2705-2723.

Schär, C., D. Lüthi, U. Beyerle, and E. Heise, 1999: The soil-precipitation feedback: A process study with a regional climate model. *J. Climate*, **12**, 722-741

Seneviratne, S.I., J.S. Pal, E.A.B. Eltahir, and C. Schär, 2002: Summer dryness in a warmer climate: A process study with a regional climate model. *Climate Dyn.*, in press

Seneviratne, S.I., P. Viterbo, D. Lüthi, and C. Schär, 2003: Inferring changes in terrestrial water storage using ERA-40 reanalysis data: The Mississippi river basin. *J. Climate*, in preparation.

Simmons, A.J., and J.K. Gibson, 2000: The ERA-40 Project Plan. ERA-40 Project Report Series, No. 1, 62 pp. Available from ECMWF.

Starr, V.P., and J. Peixoto, 1958: On the global balance of water vapor and the hydrology of deserts. *Tellus*, **10**, 189-194.

Trenberth K.E., and C.J. Guillemot, 1995: Evaluation of the global atmospheric moisture budget as seen from analyses. *J. Climate*, **8**, 2255-2272.

Wahr, J., M. Molenaar, and F. Bryan, 1998: Time-variability of the Earth's gravity field: Hydrological and oceanic effects and their possible detection using GRACE. *J. Geophys. Res.*, **103** (B12), 30, 205-230.

Wetherald R.T., and Manabe S., 1999: Detectability of summer dryness caused by greenhouse warming. Clim. Change, 43, 495-511.

Yeh, P.J.F., M. Irizarry, E.A.B. Eltahir, 1998: Hydroclimatology of Illinois: A comparison of monthly evaporation estimates based on atmospheric water balance and soil water balance. *J. Geophys. Res.*, **103** (D16), 19,823-19,837.